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14. ABSTRACT

15. SUBJECT TERMS

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UU	UU	UU	UU		Daniel Gauthier
					19b. TELEPHONE NUMBER 919-660-2511

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RPPR Final Report
as of 21-Feb-2019

Agency Code:

Proposal Number: 61405NS **Agreement Number: W911NF-12-1-0099**

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DUNS Number: 044387793 EIN: 560532129

Report Date: 20-Jan-2019 Date Received: 29-Oct-2018
Final Report for Period Beginning 14-Mar-2012 and Ending 20-Oct-2018
Title: Fundamental Experimental Research on the Dynamics of Physical Networks
Begin Performance Period: 14-Mar-2012 **End Performance Period:** 20-Oct-2018
Report Term: 0-Other
Submitted By: Daniel Gauthier Email: gauthier@phy.duke.edu
Phone: (919) 660-2511
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4 **STEM Participants:** 0

Major Goals: Objective: We undertook a broad experimental program in fundamental network science. We used a revolutionary experimental approach to observe and analyze the evolution of complex dynamical networks such as pattern formation and control, emergence of complexity, and information processing. Specifically, we studied time-delayed Boolean networks implemented experimentally with logic gates on field-programmable gate arrays (FPGAs). We used this experimental platform to create diverse networks of various sizes that display periodic, chaotic, and excitable dynamics and we applied what we learned about these networks to perform information processing and performed more detailed studies of the ultra-long transient behavior of relatively simple networks that have implications for biological networks. In addition, we have explored methods for solving constraint satisfaction problems using autonomous Boolean networks on an FPGA.

Approach: We used a balanced approach combining mathematical modeling and experiments with a reconfigurable chip [field-programmable gate array (FPGA)]. First, we devised a Boolean analogy to a given physical phenomenon occurring in networks (e.g., chaos, excitability, phase locking, synchronization patterns…). Then we designed an experimental setup that is a physical embodiment of the Boolean analogy. Finally, we developed mathematical models (e.g., Boolean delay equations (BDE), Glass models, etc.) to analyze and interpret our experimental findings. The work was in collaboration with Profs. Michelle Girvan and Edward Ott at the University of Maryland and Prof. Eckehard Schöll of the Technical University of Berlin, Germany.

Relevance to Army: Our fundamental network science research provides three potential applications for the Army. First, we developed analog neuro-inspired computation machines based on our Boolean neural-like networks. We showed that our Boolean neurons operate at a nanosecond time scale (millions of times faster than biological neurons), thus opening new avenues in the field of pattern recognition (e.g., speech, image, automatic threat detection) integrated on a hardware platform. Second, our fundamental research on chaotic dynamics generated by hardware-efficient networks can be used to generate random number in a massively parallel fashion: Thanks to scalability of FPGAs, we can potentially achieve physical random number generation at ultra-high rates of Tb/s on a single electronic platform. This would be invaluable for the generation of secure keys used in cryptographic protocols or benefit to the simulation of extremely complex systems (e.g., particle accelerators, nuclear reactors, bioengineered systems). Finally, our platform can be used to study fundamental aspects of control of complex networks by making small adjustment to network parameters. For our Boolean-like networks, control is typically accomplished by adjusting the timing of signals along the network links or by injecting Boolean spatial-temporal patterns into the network.

Accomplishments: See attached report.

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Training Opportunities: The graduate students and post-docs involved with this project presented their work at international conferences. Also, they were highly engaged in developing new programs with collaborators at TU Berlin, U of Maryland, and will Potomac Research LLC.

Results Dissemination: See attached report.

Honors and Awards: Dr. David Rosin's Ph.D. dissertation, entitled "Dynamics of complex autonomous Boolean networks," TU Berlin and Duke University, was co-selected as the best physics Ph.D. dissertation by the European Physics Society in 2015 and was published by Springer in their Theses series and has been downloaded over 4,870 times at this time. Rosin's thesis sets the foundation for this new field and demonstrates the great flexibility offered by the FPGA-based experimental platform for studying the fundamental behavior of complex networks.

Protocol Activity Status:

Technology Transfer: * We have partnered with Potomac Research, LLC to apply for SBIR and STTR funding based on the work developed in this program. We have a 100% success rate in our applications for the following projects:

1. 'RAD: Reservoir-based Anomaly Detection,' Potomac Research LLC (SBIR Phase I, Army Research Office, Topic #A18-034), 9 Jul 18 – 8 May 23.

2. 'Provably Unclonable Functions on Field Programmable Gate Arrays,' Potomac Research LLC (STTR Phase I, Army Research Office, Topic #A18B-T001),1 Jan 19 – 30 Jun 19.

3. 'Software solutions for true random number generation,' Potomac Research LLC (SBIR Phase I, Army Research Office, Topic #A18-116), 1 Jan 19 – 30 Jun 19.

* In collaboration with D. Lathrop (PI), M. Girvan, and E. Ott, we have started a long-term program with the Laboratory for Telecommunication Science on 'Reservoir computing for identifying radio-frequency signals.'

* We have filed two patent disclosures through Ohio State University related to this program. Potomac Research LLC as well as several other companies have expressed interest in this intellectual property:

1. D. Canaday, A. Griffith, and D. Gauthier, 'Rapid Time-Series Prediction with an FPGA-Based Reservoir Computer.'

2. D. Canaday, A. Griffith, D. Gauthier, and A. Pomerance, 'Method for Precise, Model-Free Control of Dynamical Systems with a Deep Reservoir Computer.'

* Ford Motor Company has expressed interest in using RCs for forecasting and controlling engine dynamics based on the noisy telemetry signals generated by field-deployed vehicles. We have applied for funding for this project though the Ford-Ohio State University Alliance program.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Daniel Gauthier
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Faculty
Participant: Gregory Lafyatis

Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Damien Rontani
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Otti D'Huys
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Participant: Johannes Lohmann
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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)

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Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

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Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Aaron Griffith
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 5-Submitted
Journal: Europhysics Letters
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: 10/4/18 12:00AM Date Published:
Publication Location:
Article Title: Excitability in autonomous Boolean networks
Authors: D. P. Rosin, D. Rontani, D. J. Gauthier, and E. Schöll
Keywords: Boolean networks, excitable systems, neural dyanmics
Abstract: We demonstrate theoretically and experimentally that excitable systems can be built with autonomous Boolean networks. Their experimental implementation is realized with asyn- chronous logic gates on a reconfigurabe chip. When these excitable systems are assembled into time-delay networks, their dynamics display nanosecond time-scale spike synchronization patterns that are controllable in period and phase.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 5-Submitted
Journal: Physical Review Letters (submitted)
Publication Identifier Type: Other Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: 10/4/18 12:00AM Date Published:
Publication Location:
Article Title: Control of synchronization patterns in neural-like Boolean networks
Authors: D. P. Rosin, D. Rontani, D. J. Gauthier, and E. Schöll
Keywords: Boolean networks, synchronization, neural dynamics
Abstract: We study experimentally the synchronization patterns in time-delayed directed Boolean networks of excitable systems. We observe a transition in the network dynamics when the refractory time of the individual systems is adjusted. When the refractory time is on the same order-of-magnitude as the mean link time delays or the heterogeneities of the link time delays, cluster synchronization patterns change, or are suppressed entirely, respectively. We also show that these transitions occur when we only change the properties of a small number of nodes identifed by their larger in-degree, hence the synchronization patterns can be controlled locally by these nodes. Our findings have implications for synchronization in biological neural networks.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: EPL (Europhysics Letters)
Publication Identifier Type: DOI Publication Identifier: 10.1209/0295-5075/100/30003
Volume: 100 Issue: 3 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Excitability in autonomous Boolean networks
Authors:
Keywords: excitable system, Boolean network, complex network, time-delay network
Abstract: We demonstrate theoretically and experimentally that excitable systems can be built with autonomous Boolean networks. Their experimental implementation is realized with asynchronous logic gates on a reconfigurabe chip. When these excitable systems are assembled into time-delay networks, their dynamics display nanosecond time scale spike synchronization patterns that are controllable in period and phase.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.110.104102
Volume: 110 Issue: 10 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Control of Synchronization Patterns in Neural-like Boolean Networks
Authors:
Keywords: synchronization, complex networks, neural networks, cluster synchronization, control
Abstract: We study experimentally the synchronization patterns in time-delayed directed Boolean networks of excitable systems. We observe a transition in the network dynamics when the refractory time of the individual systems is adjusted. When the refractory time is on the same order of magnitude as the mean link time delays or the heterogeneities of the link time delays, cluster synchronization patterns change, or are suppressed entirely, respectively. We also show that these transitions occur when we change the properties of only a small number of driver nodes identified by their larger in degree; hence, the synchronization patterns can be controlled locally by these nodes. Our findings have implications for synchronization in biological neural networks.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
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Volume: 87 Issue: 4 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Ultrafast physical generation of random numbers using hybrid Boolean networks
Authors:
Keywords: random number generation, complex networks, Boolean networks, chaos, logic gates
Abstract: We describe a high-speed physical random number generator based on a hybrid Boolean network with autonomous and clocked logic gates, realized on a reconfigurable chip. The autonomous logic gates are arranged in a bidirectional ring topology and generate broadband chaos. The clocked logic gates receive input from the autonomous logic gates so that random numbers are generated physically that pass standard randomness tests without further postprocessing. The large number of logic gates on reconfigurable chips allows for parallel generation of random numbers, as demonstrated by our implementation of 128 physical random number generators that achieve a real-time bit rate of 12.8 Gbits/s.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Chaos: An Interdisciplinary Journal of Nonlinear Science
Publication Identifier Type: DOI Publication Identifier: 10.1063/1.4807481
Volume: 23 Issue: 2 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Experiments on autonomous Boolean networks
Authors:
Keywords: autonomous Boolean networks, complex networks, chaos, phase oscillator, excitable dynamics
Abstract: We realize autonomous Boolean networks by using logic gates in their autonomous mode of operation on a field-programmable gate array. This allows us to implement time-continuous systems with complex dynamical behaviors that can be conveniently interconnected into large-scale networks with flexible topologies that consist of time-delay links and a large number of nodes. We demonstrate how we realize networks with periodic, chaotic, and excitable dynamics and study their properties. Field-programmable gate arrays define a new experimental paradigm that holds great potential to test a large body of theoretical results on the dynamics of complex networks, which has been beyond reach of traditional experimental approaches.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
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Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.95.022211
Volume: 95 Issue: 2 First Page #: 022211
Date Submitted: 8/16/17 12:00AM Date Published: 2/1/17 5:00AM
Publication Location:
Article Title: Transient dynamics and their control in time-delay autonomous Boolean ring networks
Authors: Johannes Lohmann, Otti D'Huys, Nicholas D. Haynes, Eckehard Schöll, Daniel J. Gauthier
Keywords: Boolean networks, supertransient dynamics, time-delay networks, field-programmable gate array
Abstract: Biochemical systems with switch-like interactions, such as gene regulatory networks, are well modeled by autonomous Boolean networks. Specifically, the topology and logic of gene interactions can be described by systems of continuous piecewise-linear differential equations, enabling analytical predictions of the dynamics of specific networks. However, most models do not account for time delays along links associated with spatial transport, mRNA transcription, and translation. To address this issue, we have developed an experimental test bed to realize a time-delay autonomous Boolean network with three inhibitory nodes, known as a repressilator, and use it to study the dynamics that arise as time delays along the links vary. We observe various nearly periodic oscillatory transient patterns with extremely long lifetime, which emerge in small network motifs due to the delay, and which are distinct from the eventual asymptotically stable periodic attractors.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review E
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevE.95.022211
Volume: 95 Issue: 2 First Page #: 022211
Date Submitted: 8/16/17 12:00AM Date Published: 2/1/17 5:00AM
Publication Location:
Article Title: Transient dynamics and their control in time-delay autonomous Boolean ring networks
Authors: Johannes Lohmann, Otti D'Huys, Nicholas D. Haynes, Eckehard Schöll, Daniel J. Gauthier
Keywords: Boolean networks, time-delay networks, supertransient dynamics, field-programmable gate array
Abstract: Biochemical systems with switch-like interactions, such as gene regulatory networks, are well modeled by autonomous Boolean networks. Specifically, the topology and logic of gene interactions can be described by systems of continuous piecewise-linear differential equations, enabling analytical predictions of the dynamics of specific networks. However, most models do not account for time delays along links associated with spatial transport, mRNA transcription, and translation. To address this issue, we have developed an experimental test bed to realize a time-delay autonomous Boolean network with three inhibitory nodes, known as a repressilator, and use it to study the dynamics that arise as time delays along the links vary. We observe various nearly periodic oscillatory transient patterns with extremely long lifetime, which emerge in small network motifs due to the delay, and which are distinct from the eventual asymptotically stable periodic attractors.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: SIAM News
Publication Identifier Type: Other Publication Identifier:
Volume: 51 Issue: 2 First Page #: 12
Date Submitted: 3/20/18 12:00AM Date Published: 3/1/18 10:00AM
Publication Location:
Article Title: Reservoir computing: Harnessing a universal dynamical system
Authors: Daniel J. Gauthier
Keywords: Reservoir computing, machine learning, dynamical systems, forecasting
Abstract: There is great current interest in developing artificial intelligence algorithms for processing massive data sets, often for classification tasks such as recognizing a face in a photograph. But what if our goal is to learn a deterministic dynamical system? Relevant applications include forecasting the weather, controlling complex dynamical systems, and fingerprinting radio-frequency transmitters to secure the internet of things. Training a "universal" dynamical system to predict the dynamics of a desired system is one approach to this problem that is well-suited for a reservoir computer (RC): a recurrent artificial neural network for processing time-dependent information
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 4-Under Review
Journal: Chaos
Publication Identifier Type: Other Publication Identifier:
Volume: Issue: First Page #:
Date Submitted: 10/4/18 12:00AM Date Published:
Publication Location:
Article Title: Rapid Time Series Prediction with a Hardware-Based Reservoir Computer,
Authors: D. Canaday, A. Griffith, and D.J. Gauthier
Keywords: reservoir computing, field-programmable gate array, time series prediction
Abstract: Reservoir computing is a neural network approach for processing time-dependent signals that has seen rapid development in recent years. We present here a reservoir computing scheme that has rapid processing speed both by the reservoir and the output layer. The reservoir is realized by an autonomous, time-delay, Boolean network configured on a field-programmable gate array. We investigate the dynamical properties of the network and observe the fading memory property that is critical for successful reservoir computing. We demonstrate the utility of the technique by training a reservoir to learn the short- and long-term behavior of a chaotic system. We find accuracy comparable to state-of-the-art software approaches of similar network size, but with a superior real-time prediction rate up to 160 MHz.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

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Publication Type: Thesis or Dissertation
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Date Received: 22-Aug-2014 Completion Date:
Title: Dynamics of complex autonomous Boolean networks
Authors:
Acknowledged Federal Support:

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as of 21-Feb-2019

Final Progress Report - Grant W911NF-12-1-0099
(Reporting Period: March 14, 2012 – October 20, 2018)

Fundamental Experimental Research on the Dynamics of Physical Networks

Daniel J. Gauthier
Physics Department
Duke University, Durham, NC 27708

Objective

We undertook a broad experimental program in fundamental network science. We used a revolutionary experimental approach to observe and analyze the evolution of complex dynamical networks such as pattern formation and control, emergence of complexity, and information processing. Specifically, we studied time-delayed Boolean networks implemented experimentally with logic gates on field-programmable gate arrays (FPGAs). We used this experimental platform to create diverse networks of various sizes that display periodic, chaotic, and excitable dynamics and we applied what we learned about these networks to perform information processing and performed more detailed studies of the ultra-long transient behavior of relatively simple networks that have implications for biological networks. In addition, we have explored methods for solving constraint satisfaction problems using autonomous Boolean networks on an FPGA.

Approach

We used a balanced approach combining mathematical modeling and experiments with a reconfigurable chip [field-programmable gate array (FPGA)]. First, we devised a Boolean analogy to a given physical phenomenon occurring in networks (*e.g.*, chaos, excitability, phase locking, synchronization patterns…). Then we designed an experimental setup that is a physical embodiment of the Boolean analogy. Finally, we developed mathematical models (*e.g.*, Boolean delay equations (BDE), Glass models, etc.) to analyze and interpret our experimental findings. The work was in collaboration with Profs. Michelle Girvan and Edward Ott at the University of Maryland and Prof. Eckehard Schöll of the Technical University of Berlin, Germany.

Relevance to Army

Our fundamental network science research provides three potential applications for the Army. First, we developed analog neuro-inspired computation machines based on our Boolean neural-like networks. We showed that our Boolean neurons operate at a nanosecond time scale (millions of times faster than biological neurons), thus opening new avenues in the field of pattern recognition (*e.g.*, speech, image, automatic threat detection) integrated on a hardware platform. Second, our fundamental research on chaotic dynamics generated by hardware-efficient networks can be used to generate random number in a massively parallel fashion: Thanks to scalability of FPGAs, we can potentially achieve physical random number generation at ultra-high rates of Tb/s on a single electronic platform. This would be invaluable for the generation of secure keys used in cryptographic protocols or benefit to the simulation of extremely complex systems (*e.g.*, particle accelerators, nuclear reactors, bioengineered systems). Finally, our platform can be used to study fundamental aspects of control of complex networks by making small adjustment to network parameters. For our Boolean-like networks, control is typically accomplished by adjusting the timing of signals along the network links or by injecting Boolean spatial-temporal patterns into the network.

Personnel

During this course of this program, the following researchers were active participants on this project:

- Dr. Daniel J. Gauthier (PI, currently Research Professor of Physics at Duke University and Professor of Physics at Ohio State University)
- Dr. Gregory P. Lafyatis (PI of sub-award with Ohio State University, Professor of Physics, Ohio State University)
- Dr. Damien Rontani (Post-doc, 2012-2013, currently Assistant Professor, École Supérieure d'Électricité, Supélec, France)
- Dr. Otti D'Huys (Post-doc, 2014-2016, currently Lecturer in Mathematics, Aston University, UK)
- Dr. David P. Rosin (physics Ph.D. obtained in 2014, dissertation research supported by this project, currently Software development engineer, Finisar, Berlin, Germany)
- Mr. Nicholas D. Haynes (physics M.S. obtained in 2017, currently Director of Data Science, Automated Insights, Durham, NC)
- Mr. Johannes Lohmann (physics M.Sc., TU Belin, obtained in 2015, currently graduate research assistant at the University of Copenhagen, Denmark)
- Mr. Stefan Apostel (physics M.Sc., TU Berlin, obtained in 2017, currently Web Engineer, INWX GmbH, Brandenburg, Germany)
- Mr. Daniel Canaday (currently a graduate research assistant at Ohio State University working on this project)
- Mr. Aaron Griffith (currently a graduate research assistant at Ohio State University working on this project)

Summary of Major Accomplishments

The major outcome of our program is starting an entirely new field of studying complex networks using field-programmable gate arrays (FPGAs). We have demonstrated that the flexibility and reprogrammable aspect of the chips allows us to study a wide range of network behaviors. For example, by grouping logic elements in a systematic way, we realize a neuron with excitable and refractory behaviors. By grouping logic elements in loops, we realize a phase oscillator, which can be coupled to observe synchronization or, in larger arrays, chimera states. Finally, these complex networks are an ideal platform for studying information flow and processing via the networks to realize a so-called reservoir computer. We far exceeded the goals set out in the original proposal for this program.

Dr. David Rosin's Ph.D. dissertation, entitled "Dynamics of complex autonomous Boolean networks," TU Berlin and Duke University, was co-selected as the best physics Ph.D. dissertation by the European Physics Society in 2015 and was published by Springer in their Theses series and has been downloaded over 4,870 times at this time. Rosin's thesis sets the foundation for this new field and demonstrates the great flexibility offered by the FPGA-based experimental platform for studying the fundamental behavior of complex networks.

This program is generating considerable interest beyond the primary work described here. Together with collaborators at Duke University, the University of Maryland, and Harvard University, we further emphasized our research on a new approach to machine learning known as reservoir computing through a seedling grant from DARPA and passed through this project. A reservoir computer is an artificial neural network based on an internal complex network (the reservoir), which is an autonomous dynamical system, and is well suited for predicting, forecasting, and controlling dynamical systems. We are undertaking other research projects for the US Army through SBIR and STTR projects in collaboration with a small startup company, Potomac Research LLC. Also, in collaboration with the University of Maryland, we have a long-term project on using reservoir computers for identifying radio-frequency communications, funded by the Laboratory for Telecommunication Sciences. Finally, we are initiating a project with Ford Motor Company for assessing and controlling engine dynamics using reservoir computers.

A brief summary of specific accomplishments is given here.

- Demonstrated that a single excitable artificial neuron with a controllable refractory time can be realized by group together a small collection of logic elements on an FPGA. The node displays self-pulsation when the input is held high.
- Observed synchronization of two delay-coupled networks where each contains a single excitable node.
- Realized intermediate-scale artificial neuronal networks (~100 nodes) consisting of Boolean excitable nodes with random topology and community structure.
- Observed that synchronization patterns can be altered and controlled in the artificial neuronal networks similar to those described in simple networks with unidirectional loops. These types of networks are the largest experimental neural-like network built to date without a computer to handle the coupling.
- Created a novel Boolean phase oscillator with periodic dynamics capable of exhibiting synchronization behavior analogous to those described by coupled phase oscillators with variable coupling strength. Observe Arnold-tongue-like behavior when changing the synchronization coupling strength.
- Created an intermediate-scale network of Boolean phase oscillators, demonstrating an analogy to the well-known Kuramoto oscillator network. Observe chimera states, a super-transient behavior on the route to full network synchronization. During the transient, which can persist for billions of characteristic time scales of the oscillators, the chimera states wander through the network, the first observation of this behavior.
- Built an operational reservoir computer on an FPGA using a single digital logic element with time-delay feedback and showed that it is able to learn to distinguish temporal patterns. This demonstrates the feasibility of using autonomous Boolean networks realized on FPGAs to do fast information processing.
- Studied ultra-long transient dynamics of simple time-delay autonomous Boolean networks. We observed chaotic transients that survived up to 10^{10} characteristic time scales in systems of a single exclusive-OR (XOR) gate with time-delay feedback and small (2- and 3-node) rings of NOT gates with time-delay connections. The fast time scale of the systems (~1 ns) allowed us to collect statistics on these long transients. This network is a simple model of a gene regulatory network (known as a repressilator) that may be a model for a biological clock.
- Realized an operational reservoir computer on an FPGA using a large autonomous Boolean network consisting of over 100 nodes. We used the reservoir computer to solve a standard machine learning task for automated recognition of hand-written digits. In particular, we used the so-called MNIST data set, which includes a large number of images of hand-written digits that are used as a training data set, and a related independent set that is used to test the generalizability of the reservoir computer. We

obtain close to state-of-the-art performance when compared to competing deep learning methods for the case when no off-line preprocessing of the images is undertaken.

- Developed computer code to simulate a discrete time reservoir computer, the approach taken by most other groups in the world who are studying reservoir computers. Using this code, we find that the Boolean nature of the reservoir nodes (as opposed to a continuous-value smooth nonlinear input-output node) only slightly degrades the performance of the reservoir computer. Furthermore, we find that our experimental autonomous Boolean network out-performs the discrete-time network for fixed reservoir resources (*e.g*., number of nodes).
- Applied new FPGA technologies to fundamental network science. One challenge in studying large networks it to be able to read out the dynamics of the network on a fast enough time scale; this was posed as a problem that needed to be solved in our original proposal. We have developed methods to sample the network dynamics in real time using the FPGA resources (sample and hold, local memory, deserializers) to essentially solve this problem without having to use an external oscilloscope. This greatly simplifies experiments on autonomous Boolean networks.
- Develop cloud-based distributed computing approaches using the Open Science Grid so that we can conduct many experiments in an automated fashion and on many parallel FPGA demonstration boards. Finally, we are transitioning our work to a new family of FPGAs that have a hard processor on the same chip with high-speed communication between the FPGA and the CPU. This greatly facilitates transfer of data to and from the FPGA and will make FPGAs more accessible to researchers who are more familiar with standard programming on a CPU or GPU.
- Developed a high-speed classification layer for a FPGA-based reservoir computer allowing up to obtain world-record results for using a reservoir computing to predict the evolution of a dynamical system
- Found that there are linear dependencies between the dynamics of reservoir nodes, allowing us to substantially compress the size of the reservoir while maintaining prediction accuracy
- Applied the concept of a deep reservoir computer to control fixed-points and periodic orbits of dynamical system
- Demonstrated that a reservoir computer can detect anomalies in dynamical systems and applied this to the specific problem of detecting degradation of a helicopter gear box

Collaborations and Technology Transfer

- We have partnered with Potomac Research, LLC to apply for SBIR and STTR funding based on the work developed in this program. We have a 100% success rate in our applications for the following project:
  1. 'RAD: Reservoir-based Anomaly Detection,' Potomac Research LLC (SBIR Phase I, Army Research Office, Topic #A18-034), 9 Jul 18 – 8 May 23.
  2. 'Provably Unclonable Functions on Field Programmable Gate Arrays,' Potomac Research LLC (STTR Phase I, Army Research Office, Topic #A18B-T001),1 Jan 19 – 30 Jun 19.
  3. 'Software solutions for true random number generation,' Potomac Research LLC (SBIR Phase I, Army Research Office, Topic #A18-116), 1 Jan 19 – 30 Jun 19.
- In collaboration with D. Lathrop (PI), M. Girvan, and E. Ott, we have started a long-term program with the Laboratory for Telecommunication Science on 'Reservoir computing for identifying radio-frequency signals.'

- We have filed two patent disclosures through Ohio State University related to this program. Potomac Research LLC as well as several other companies have expressed interest in this intellectual property:
    1. D. Canaday, A. Griffith, and D. Gauthier, ‘Rapid Time-Series Prediction with an FPGA-Based Reservoir Computer.’
    2. D. Canaday, A. Griffith, D. Gauthier, and A. Pomerance, ‘Method for Precise, Model-Free Control of Dynamical Systems with a Deep Reservoir Computer.’
- Ford Motor Company has expressed interest in using RCs for forecasting and controlling engine dynamics based on the noisy telemetry signals generated by field-deployed vehicles. We have applied for funding for this project though the Ford-Ohio State University Alliance program.

Journal Publications Resulting from this Program

- D.P. Rosin, D. Rontani, D.J. Gauthier, and E. Schöll, "Excitability in autonomous Boolean networks," Europhys. Lett. **100**, 30003 (2012).
- D. Rosin, D. Rontani, D.J. Gauthier and E. Schöll, "Control of Synchronization Patterns in Neural-like Boolean Networks," Phys. Rev. Lett. **110**, 104102 (2013).
- D. Rosin, D. Rontani and D.J. Gauthier, "Ultrafast Physical Generation of Random Numbers Using Hybrid Boolean Networks," Phys. Rev. E. **87**, 040902(R) (2013).
- D. Rosin, D. Rontani, D.J. Gauthier and E. Schöll, "Experiments on Autonomous Boolean Networks," Chaos **23**, 025102 (2013).
- H. L. D. de S. Cavalcante, M. Oriá, D. Sornette, E. Ott, and D. J. Gauthier, 'Predictability and suppression of extreme events in a chaotic system,' Phys. Rev. Lett. **111**, 198701 (2013).
- D.P. Rosin, D. Rontani, and D.J. Gauthier, 'Synchronization of coupled Boolean phase oscillators,' Phys. Rev. E **89**, 042907 (2014).
- D.P. Rosin, D. Rontani, N.D. Haynes, E. Schöll and D.J. Gauthier, 'Transient scaling and resurgence of chimera states in coupled Boolean phase oscillators,' Phys. Rev. E **90**, 030902 (2014).
- N. D. Haynes, M. C. Soriano, D. P. Rosin, I. Fischer, D. J. Gauthier, ‘Reservoir computing with a single time-delay autonomous Boolean node,’ Phys. Rev. E **91**, 020801 (2015).
- R. R. Rivera-Durón, E. Campos-Cantón, I. Campos-Cantón, and D. J. Gauthier, ‘Forced synchronization of autonomous Boolean networks,’ Chaos **25**, 083113 (2015).
- O. D'Huys, J. Lohmann, N. D. Haynes, and D. J. Gauthier, 'Transient scaling in autonomous Boolean network motifs,' Chaos **26**, 4954274 (2016).
- J. Lohmann, O. D’Huys, N. D. Haynes, E. Schöll, and D. J. Gauthier, ‘Transient dynamics and their control in time-delay autonomous Boolean ring networks,’ Phys. Rev. E **95**, 022211 (2017).
- D. Canaday, A. Griffith, and D.J. Gauthier, ‘Rapid Time Series Prediction with a Hardware-Based Reservoir Computer,’ submitted for publication to Chaos (2018). (arXiv:1807.07627).

Other Publication Resulting from this Program

- D.J. Gauthier, ‘Reservoir computing: Harnessing a universal dynamical system,’ SIAM News **51**:2, 12 (2018).

Presentations, Colloquia, and Seminars Delivered During the Reporting Period

* denotes invited presentation

- D.J. Gauthier, D. P. Rosin, and D. Rontani, *’Dynamics of autonomous Boolean networks,’ Departament de Fisica i Enginyeria Nuclear, Universitat Politicnica de Catalunya, Terrassa, Spain, Mar. 22, 2012.
- D. P. Rosin, D. Rontani, D.J. Gauthier, and E. Schöll, ‘Experiments on large networks of excitable time-delay Boolean circuits,’ Poster at International Conference on Delayed Complex Systems, Palma de Mallorca, Spain, Jun. 4-8, 2012.
- D.J. Gauthier, D. P. Rosin, and D. Rontani, *’Dynamics of large-scale autonomous time-delay Boolean networks,’ International Conference on Delayed Complex Systems, Palma de Mallorca, Spain, Jun. 4-8, 2012.
- D. Rontani, D. P. Rosin, D. Gauthier, and E. Schöll *’Autonomous Time-Delayed Boolean Networks Using FPGAs,’ 2012 International Symposium on Nonlinear Theory and its Applications, Palma de Mallorca, Spain, Oct. 24, 2012.
- D.J. Gauthier, *’Predictability and control of extreme events in complex systems,’ Applied Dynamics Seminar, University of Maryland, College Park, MD, Dec. 6, 2012.
- D.J. Gauthier, ‘Predictability and control of extreme events in complex systems,’ Dynamics Days 2013, Denver, CO, Jan. 3-6, 2013.
- D. P. Rosin, D. Rontani, D. J. Gauthier, and E. Schöll, ‘Control of synchronization patterns in neural-like Boolean networks,’ Dynamics Days 2013, Denver, CO, Jan. 3-6, 2013.D. P. Rosin, D. Rontani, D. J. Gauthier, and E. Schöll, ‘Control of synchronization patterns in neural-like Boolean networks,’ CCNR Seminar, Boston, MA, March 28, 2013.
- D. P. Rosin, D. Rontani, D. J. Gauthier, and E. Schöll, ‘Control of synchronization patterns in neural-like Boolean networks,’ Dynamics Days Europe 2013, Madrid, May 3-7, 2013.
- D.J. Gauthier, D.P. Rosin, and D. Rontani, ‘Tutorial on Autonomous Time-Delay Boolean Networks,’ WISeNet Workshop, Durham, NC, Jun. 6, 2013.
- D. Rontani, S.D. Cohen, A. Aragoneses, C. Masoller, M.C. Torrent and D.J. Gauthier, ‘Laser-based dynamical sensor resolving two-dimensional translation at the nanoscale,’ International Symposium on Physics and Application of Laser Dynamics (IS-PALD 2013), Paris, France, Oct. 28-31, 2013.
- D. P. Rosin, D. Rontani, E. Schöll, and, D. J. Gauthier, ‘Experimental signatures of chimera states in non-locally coupled Boolean phase oscillators,’ Dynamics Days US 2014, Atlanta, GA, Jan 2-5, 2014.
- N.D. Haynes, D. P. Rosin, D. Rontani, and D. J. Gauthier, ‘Towards reservoir computing with time-delay autonomous Boolean networks,’ Poster presented at Dynamics Days US 2014, Atlanta, GA, Jan 2-5, 2014.
- N. D. Haynes, D. P. Rosin, M. C. Soriano, I. Fischer, and D. J. Gauthier, ‘Reservoir computing with a single autonomous Boolean node using time-delay feedback,’ WISeNet Workshop, Durham, NC, Jun. 6, 2014.

- D. J. Gauthier, D. P. Rosin, D. Rontani, and N. D. Haynes, *’Dynamics and control of time-delay Boolean networks,’ Symposium of SFB 910: Applications of Dynamical Networks, Berlin, Germany, Jun. 20, 2014.
- D.J. Gauthier, D.P. Rosin, D. Rontani, and N. Haynes, ‘Autonomous Boolean networks for experimental network science and chimera states,’ Experimental Chaos and Complexity (ECC) Conference, Aberdeen, Scotland, Aug. 27, 2014.
- D.J. Gauthier, N.D. Haynes, J. Lohmann, O. D’Huys, and D.P. Rosin, *’Extreme transients in time-delay autonomous Boolean networks,’ Dynamics Days XXXIV, Houston, TX, Jan. 10, 2015.
- N.D. Haynes, M.C. Soriano, D.P. Rosin, I. Fischer, and D.J. Gauthier, ‘Physical reservoir computing with Boolean logic,’ Poster presented at Dynamics Days XXXIV, Houston, TX, Jan. 10, 2015.
- J. Lohmann, N.D. Haynes, O. D’Huys, E. Schöll, and D.J. Gauthier, ‘Dynamics of experimental time-delay autonomous Boolean networks,’ Poster presented at Dynamics Days XXXIV, Houston, TX, Jan. 10, 2015.O. D’Huys, J. Lohmann, N.D. Haynes and D.J. Gauthier, *’Extreme transients in autonomous time-delay Boolean networks,’ Delay differential equations in physical sciences and engineering, Fields Institute, Toronto, Canada, May 11-15, 2015.
- D.J. Gauthier, *’Dynamics of autonomous time-delay Boolean networks,’ Delay differential equations in physical sciences and engineering, Fields Institute, Toronto, Canada, May 11-15, 2015.
- O. D’Huys, N.D. Haynes, M.C. Soriano, I. Fischer, and D.J. Gauthier *’Dynamics of Autonomous Boolean Networks,’ SIAM Conference on Applications of Dynamical Systems (DS15), Snowbird, Utah, May 17-21, 2015.
- D.J. Gauthier, H. Cavalcante, M. Oria, D. Sornette, and E. Ott, *’Forecasting and Controlling Dragon-King Events in Coupled Dynamical Systems,’ SIAM Conference on Applications of Dynamical Systems (DS15), Snowbird, Utah, May 17-21, 2015.N.D. Haynes, O. D’Huys, and D.J. Gauthier, ‘Extreme transients in time-delay autonomous Boolean networks,’ poster at NetSci 2015, Zaragoza, Spain, June 3, 2015.
- D.J. Gauthier, *'Network Science: A new paradigm for understanding our complex world,' Dr. Joseph Morgan Memorial Lecture, Texas Christian University, Fort Worth, TX, Oct. 8, 2015.
- D.J. Gauthier, *'Dynamics of autonomous Boolean networks,' Physics Department Seminar, Texas Christian University, Fort Worth, TX, Oct. 9, 2015.
- D.J. Gauthier, *'Dynamics of autonomous Boolean networks,' Network Frontier Workshop 2015, Northwestern University, Evanston, IL, Dec. 6, 2015.
- D.J. Gauthier, *'A journey with Prof. Schoell: from delay oscillators to delay networks,' Symposium in honour of the 65th birthday of Eckehard Schoell, TU Berlin, Berlin, Germany, Feb. 12, 2016.
- D.J. Gauthier, *'Dynamics and control of autonomous Boolean ring networks,' Workshop on Control and Observability of Network Dynamics, Mathematical Biosciences Institute, The Ohio State University, Columbus, OH, Apr. 14, 2016.
- D.J. Gauthier, *'Dynamics of autonomous, time-delay Boolean networks with application to information processing,' 14th Experimental and Complexity Conference (ECC), University of Calgary, Banff Centre, Banff, Canada, May 16-19.

- D.J. Gauthier, 'Dynamics of Autonomous Boolean Networks,' Seminar of Excellence in Complex Systems, The Institute for Cross-Disciplinary Physics and Complex Systems (IFISC), Universitat de les Illes Balears, Palma de Mallorca, Spain, Jun. 15, 2016.
- D.J. Gauthier, D. Canaday, A. Griffith, A. Hartemink, N.D. Haynes, O. D'Huys, D. Rosin, E. Scholl, M. Girvan, B. Hunt, E. Ott, R. Brockett, *'Reservoir Computing Using Autonomous Boolean Networks,' Applied Dynamics Seminar, University of Maryland, College Park, MD, Nov. 3, 2016.
- D. Canaday, A. Griffith, D.J. Gauthier, 'Chaotic Time Series Prediction with FPGA-Based Reservoir Computers,' Dynamics Days 2017, Silver Spring, MD, Jan. 4-6, 2017
- A. Griffith, N.D. Haynes, O. D'Huys, D. Canaday, D.J. Gauthier, 'Handwritten Digit Recognition with Reservoir Computers in Software and Hardware,' Dynamics Days 2017, Silver Spring, MD, Jan. 4-6, 2017.
- D. Canaday, A. Griffith, and D.J. Gauthier, 'Control of Unknown Chaotic Systems with Reservoir Computing,' Dynamics Days 2018, Denver, CO, Jan. 4-6, 2018.
- D. Canaday, A. Griffith, and D.J. Gauthier, 'Rapid Time Series Predictions with Hardware-Based Reservoir Computing,' Wilhelm and Else Heraeus Seminar: Delayed Complex System, Bonn, Germany, July 2-5, 2018.
- D.J. Gauthier, D. Canaday, and A. Griffith, *'Reservoir computing for identifying radio-frequency communication signals and thoughts on optimizing a reservoir computer,' Applied Dynamics Seminar, University of Maryland, Apr. 26, 2018, College Park, MD.
- D.J. Gauthier, D. Canaday, and A. Griffith, *'Reservoir Computing: Harnessing a universal dynamical system,' Applied Physics Seminar, Columbia University, New York, NY, Jun. 7, 2018.
- D.J. Gauthier, D. Canaday, and A. Griffith, 'FPGA-based autonomous Boolean networks for cognitive computing,' Cognitive Computing 2018: Merging Concepts with Hardware, Hannover, Germany, Dec. 18-20, 2018.